PERFORMANCE OF THE LAGUNA PULSED POWER SYSTEM*

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Abstract

The goal of the LAGUNA experimental series of the Los Alamos National Laboratory TRAILMASTER program is to accelerate an annular aluminum plasma z-pinch to greater than one hundred kilojoules of implosion kinetic energy. To accomplish this, an electrical pulse >5.5 MA must be delivered to a 20 nH load in ~1 μs. The pulsed power system for these experiments consists of a capacitor bank for initial energy storage, a helical explosive-driven magnetic-flux compression generator for the prime power supply and opening and closing switches for power conditioning. While we have not yet achieved our design goal of 15 MA delivered to the inductive store of the system, all major components have functioned successfully at the 10 MA level. Significant successes and some difficulties experienced in these experiments are described.

Introduction

We are currently developing an explosive pulsed power system for the LAGUNA experiments of the Los Alamos National Laboratory TRAILMASTER program. The expectations for the LAGUNA experiments are presented by Greene et al.[1] in another paper in this conference. The pulsed power system makes use of an existing explosive pulsed power facility housing a 2.4-MJ capacitor bank,[2] and combines a previously tested helical explosive-driven magnetic-flux compression generator[3] with a cylindrical explosively formed fuse[4] for pulse compression. A surface discharge closing switch[5] diverts current to the load. Fig. 1 is an artist's concept of the LAGUNA apparatus.

To date, we have focused experiments on several aspects of the system. Initial experiments concentrated on maximizing the energy delivered to the helical generator from the capacitor bank, resulting in 730 kJ of the 1.2 MJ available in one-half of our capacitor bank being coupled to the generator without leading to an internal electro-mechanical failure. Subsequent generator tests ascertained the current gain of our standard generator into a 140 nH dummy load, and one experiment was devoted to testing a higher current-gain generator. With these generators in hand we conducted an initial high current test of the explosively formed fuse. The purpose of this test was to verify that the opening switch would behave as predicted from the results of small scale tests. In this test detonator actuated closing switches were used to divert current to a 10-nH static dummy load at relatively low voltage.

In the current series of sub-system tests we use surface discharge closing switches to divert current to exploding foil-fuse loads. These experiments are to verify the performance of the closing switch as part of this system and to subject the remainder of the apparatus to high voltages. Although the major components have functioned properly in these tests, we have not yet obtained satisfactory system performance due to failures in the cable transition region. The cables have been subjected separately to DC voltages of 170 kV and Marx Generator pulses of >500 kV without failure. In the system, however, after the 350 μs risetime of the pulse to ~10 MA, either cables or cable adaptors experience failures at approximately 100 kV.

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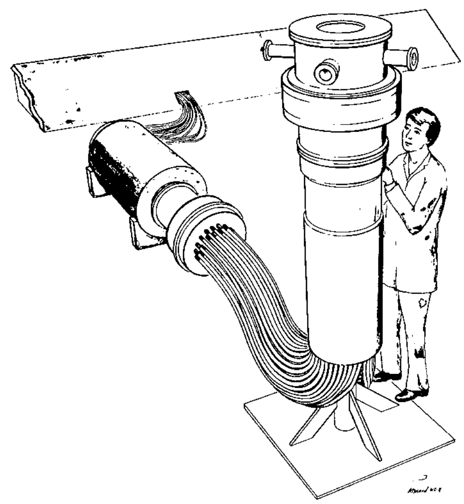

Figure 1. Artist's concept of a LAGUNA experiment. Cables to carry initial current from the capacitor bank to the generator protrude through a hole in the steel blast shield and connect to the generator. On the output of the generator is a coaxial storage inductor with adaptor to attach transmission cables. The cables (36 in this picture) carry current to the vertically mounted pulse compression/power flow/diagnostics chamber section. The explosively formed fuse opening switch is not visible inside the lower part of the cylinder. Finally, the surface discharge closing switch is depicted by the gap in the outer transmission cylinder.

Mark-IX Helical Generator Experiments

Initial predictions for the performance of the LAGUNA pulsed power system were based on the availability of a large fraction of the energy in our 2.4 MJ capacitor bank to provide the initial magnetic energy in our helical generator. However, since previous tests of our standard MK-IX helical generator were performed with only 600 kJ, we questioned the ability of the generator to function properly at such high initial energies. As a result, for the initial test, only three of the four 20-kV, 3-mF modules were used to supply the initial generator current. With this 20-kV, 9-mF capacitor bank, and a circuit dominated by the 7.2-μH initial generator inductance,[1] we expected to deliver as much as 700 kA initial current to the generator with a risetime of ~400 μs.

The curve in Fig. 2 is the dI/dt ($\dot{I}$) waveform observed on the test as the initial current was fed into the generator from the capacitor bank. This curve should be a slightly damped cosine wave, and the abrupt increase seen at ~190 μs indicates a sudden decrease in circuit inductance. Analysis indicates that such a drop would be caused by shorting consecutive turns in the high-turns-density section of the generator. The subsequent performance of the generator was also con-

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14. ABSTRACT

The goal of the LAGUNA experimental series of the Los Alamos National Laboratory TRAILMASTER program is to accelerate an annular aluminum plasma z-pinch to greater than one hundred kilojoules of implosion kinetic energy. To accomplish this, an electrical pulse)5.5 MA must be delivered to a 20 nH load in ~1 ~s. The pulsed power system for these experiments consists of a capacitor bank for initial energy storage, a helical explosive-driven magnetic-flux compression generator for the prime power supply and opening and closing switches for power conditioning. While we have not yet achieved our design goal of 15 MA delivered to the inductive store of the system, all major components have functioned successfully at the 10 MA level. Significant suc.cesses and some difficulties experienced in these experiments are described.

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sistent with a generator having reduced inductance, and whereas ~15 MA had been our desired peak current, only ~7 MA were observed.

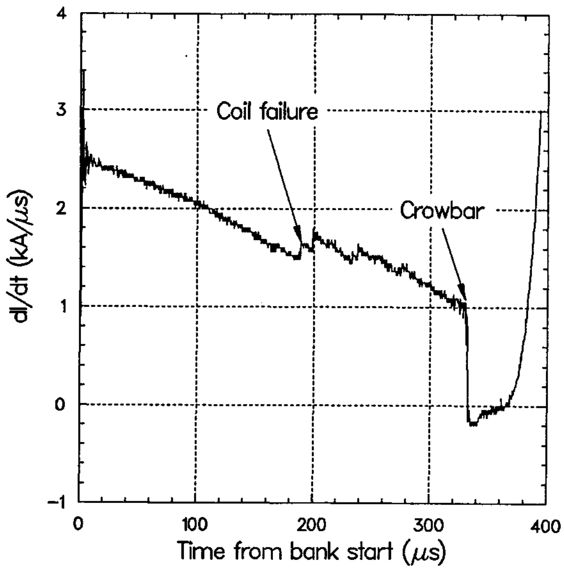

Figure 2. $\dot{I}$ from initial MK-IX generator test. The generator coil failure is indicated, as is the time when the generator crowbars at its input eliminating the capacitor bank from the circuit.

The internal failure of the MK-IX generator occurred before flux compression started. This problem led us to dramatically redesign the system for providing initial current to these high inductance generators. Our first concern was to reduce the time scale of the current feed as much as possible. To do this, we arranged two of the modules of our capacitor bank as a Marx generator as shown schematically in Fig. 3. This provided the energy of one-half the bank (1.2 MJ) in a configuration with the lumped parameters of 1.5 mF at 40 kV. Since the inductance of the generator is still dominant in the circuit, the primary effect was to reduce the capacitance by a factor of six, and hence the current risetime by a factor of 2.4. After considering damping factors, we chose to actuate the generator crowbar ~130 μs after initial current rise.

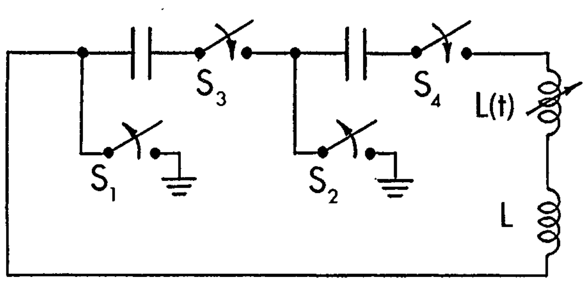

Figure 3. Circuit for putting two standard capacitor bank modules in series. Switches S_1 and S_2 are ground isolation switches that open when the bank is charged during both standard and Marx operation of the bank. Switches S_3 and S_4 are the same detonator actuated closing switches used during routine operation.

A compact header for arranging the two capacitor modules in series was devised and is pictured in Fig. 4. In normal operation, each bank module has independently triggered detonator actuated switches (S_3 and S_4), and these are retained in the Marx hookup. The tri-plate header shown in Fig. 4 is the only change from routine 2-module operation. At the tri-plate, the bottom plate is at the potential of the chassis of the low potential module and the middle plate is at the potential of the chassis of the high potential module. When switches S_3 and S_4 are closed, the high voltage side of the low potential module is connected to the center plate, and the top plate is connected to the high voltage side of the high potential module. A total of 40 kV exists between the top and bottom plates, and to suppress edge tracking with this voltage, the tri-plate is bathed in ~1 atm SF_6.

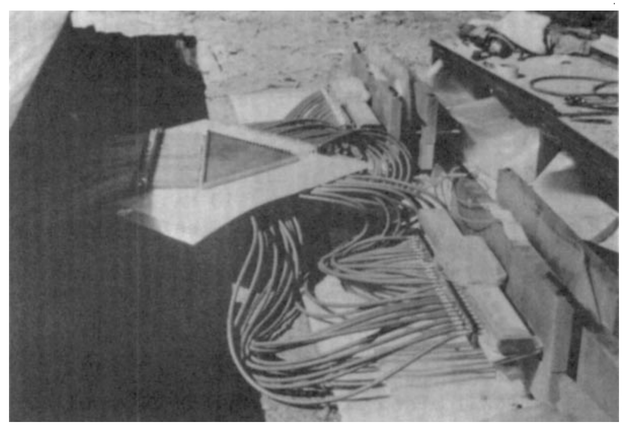

Figure 4. Tri-plate header providing series circuit for two capacitor bank modules. The standard detonator actuated bank switches (top and bottom on the right) have cable outputs that attach to the header. The ground braids from the lower right hand switch attach to the bottom plate, and the center conductor to the center plate. The ground braids from the upper switch attach to the center plate and the center conductors to the upper plate. The output cables disappear into the shadow cast by the steel blast shield, and withstand up to 40 kV when the detonator switches close. During operation, the header is enclosed in a plastic bag and bathed in SF_6.

Figure 5 shows $\dot{I}$ during the initial current phase of a MK-IX generator test using the Marx configuration. This test was performed with a total Marx voltage of 36 kV, and integration of the curve in Fig. 5 reveals that ~450 kA are delivered to the generator on these tests. This is sufficient initial current for interesting experiments, and the generator survives this pulse with no electro-mechanical failures. With this initial current, a standard MK-IX generator will drive 11 MA into a 140-nH pure inductive load. Into the complete LAGUNA pulsed power system, the MK-IX has delivered 9.5- to 10.5-MA, and the current and its respective $\dot{I}$ are shown in Fig. 6 for one of these tests. A complete discussion of the structure observed on the $\dot{I}$ curve is beyond the scope of this paper, but we note in passing that the distinct humps in the waveform are due to bifurcations in the generator windings. Although one extra test was consumed in this series in developing a dummy load that would withstand the forces of the pulse shown in Fig. 6, all tests with the Marx configuration have led to experiments with adequate generator performance.

On another test, the standard MK-IX helical winding pattern was changed to produce an 11 μH generator with fewer bifurcations. This generator was successfully tested and, as hoped, achieved a higher current gain into the 140-nH dummy load. The standard

MK-IX produces a current gain of 24 into a 140-nH load and the 11-μH generator produced a total gain of 31 in the one test. Unfortunately, the extra generator inductance reduced the initial capacitor bank current to ~350 kA, and a peak current of 11 MA was still observed. Although more current was not generated on this test, it does serve to illustrate that the MK-IX generator is not limited to 11 MA by current density considerations. We infer this because the higher gain generator produced an equivalent 11 MA output with only one half the number of parallel windings in the helix.

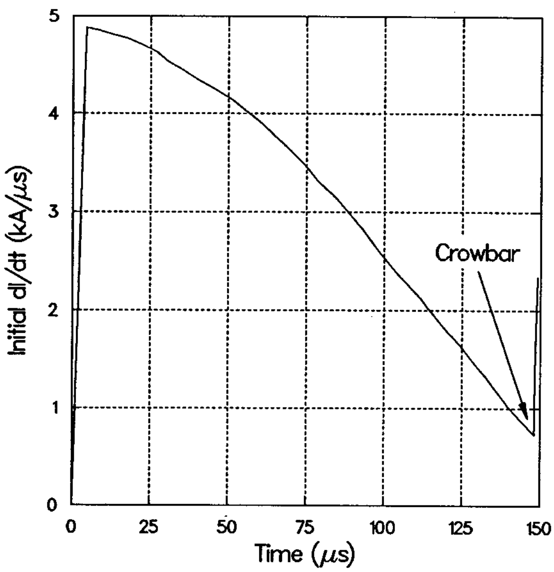

Figure 5. $\dot{I}$ from MK-IX test using Marx Header.

While we continue to examine various possibilities for generating currents of ~15 MA for future experiments, the ~10 MA currents available are interesting for further system development tests, and we have proceeded with these.

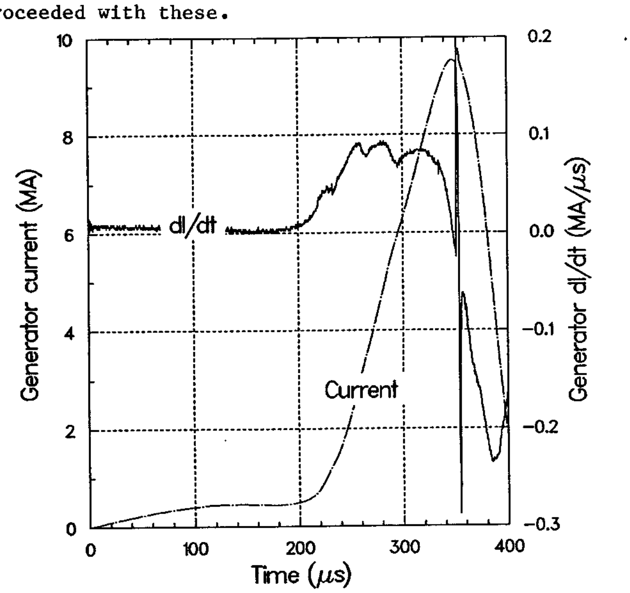

Figure 6. I and $\dot{I}$ for MK-IX test with a complete LAGUNA pulsed power system.

Opening Switch and Current Transfer Tests

With generators delivering ~10-MA to 140-nH loads in hand, we began tests of the complete pulse compression scheme. The principal component of this scheme is the explosively formed fuse (EFF) which is further discussed in another paper in this conference.[4] The EFF has previously been shown to conduct a few megamperes and to dissipate ~450 kJ[6] electrical energy in the current transfer process. To interrupt 15 MA flowing in a 35-nH opening switch and to divert the current in the storage inductor to a 20-nH load, 6 MJ must be dissipated. Our first pulse compression test was to couple a MK-IX generator to an EFF enlarged to meet this need and verify that the switch could conduct the ~350-μs pulse, then open with characteristics similar to those projected from small scale experiments. Detonator actuated closing switches were used to introduce a 10-nH static inductor in parallel with the EFF as it began to open. The switches were actuated before the EFF had developed appreciable voltage, and the only voltage generated in the test is the $L\dot{I}$ voltage that the switch generates across 10 nH. At 10-MA switch current with a 35-nH switch and a 10-nH load, 2.2 MJ must be dissipated in the switch. Figure 7 shows some of the important waveforms from the test. (These and additional curves are also shown in Ref. 4 in this conference.) After the current transfer operation, diagnostics showed that the load current was ~2 MA less than in the storage inductor and this difference has not been accounted for. Nevertheless, the resistance profile determined from this shot was in good agreement with values projected from small scale tests, and the switch had successfully conducted 9.5 MA with a risetime of ~350 μs, then interrupted it in less than 2 μs, dissipating 1.8 MJ. This test confirmed the basic switch performance.

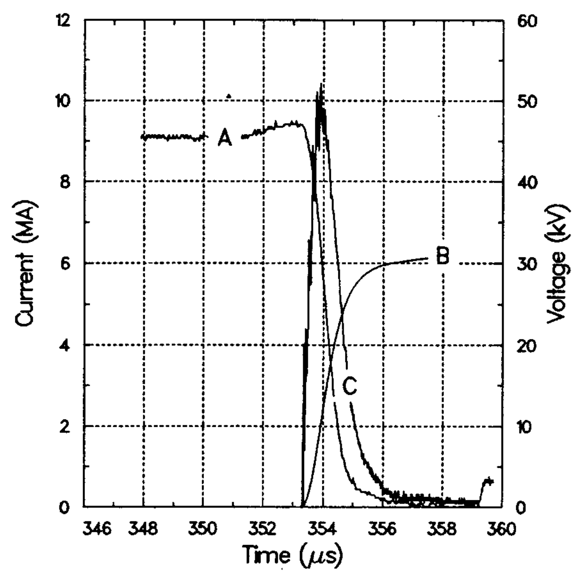

Figure 7. Explosively formed fuse current (A), load current (B), and $L\dot{I}$ voltage (C) sustained across a 10-nH fixed inductance load. Approximately 2 MA were lost to an apparent transmission line failure.

The next step was to investigate the performance of the surface discharge closing switch and to subject the system to voltages characteristic of a dynamic z-pinch load. To do this, a foil-fuse load with ~25-nH of inductance was used in place of the 10-nH static load. In addition, a surface discharge closing switch was used to introduce the fuse load into the circuit when the opening switch had developed 100 kV. On this test the system appeared to function properly in every respect until the 100 kV necessary to close the surface discharge switch were generated. At this time, or only slightly later a discrepancy began to appear among the $\dot{I}$ records. $\dot{I}$ measured in the storage inductor should equal the sum of the $\dot{I}$'s measured in the opening switch and the fuse load. After switch closure this summation failed, indicating that a failure had occurred in the cables or cable adapting hardware connecting the storage inductor to the switch/load assembly. Only ~1 MA was delivered to the fuse.

After examining the data from the first fuse-load test, we felt that the weakest part of the interconnecting cable system was the termination region where the cables connected to the base of the explosively formed fuse. Unconstrained, the cables would move a few millimeters during the current pulse, and the constraints that we could bring to bear were neither extremely massive nor strong. To alleviate this situation, the number of cables was increased from 36 to 72, and all were positioned at an increased radius. Both factors reduce the stress imposed on the cables.

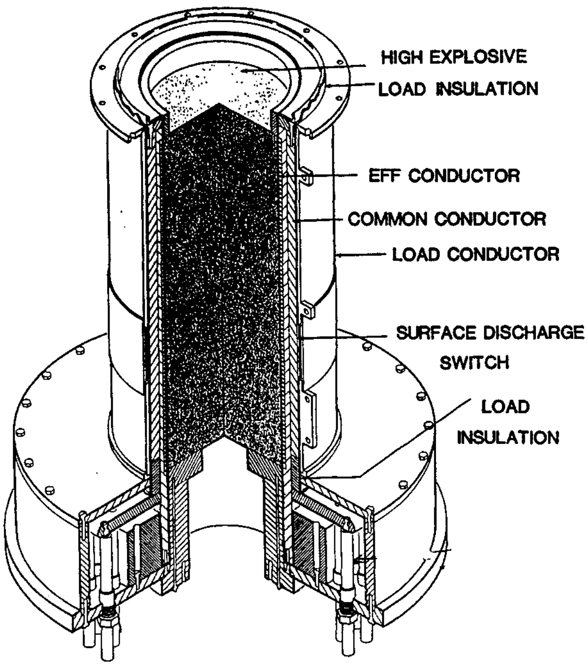

Figure 8. Explosively Formed Fuse with 72-cable transition section. As shown, the upper coax is intended to connect to a LAGUNA load. The cable adaptor region is filled with transformer oil.

Figure 8 shows the EFF and its cable input section in the 72-cable arrangement. With this arrangement, the forces would be approximately the same at 16 MA that they were on the largely successful initial system test at 9.5 MA. Figure 9 is a photograph of one of these complete assemblies on the firing pad. We have tested two such assemblies, and have yet to transfer the proper fraction of the current to the fuse load. In the first 72-cable test, ~3 of 9 MA were transferred to the fuse, and the fuse burst at a substantially lower than design current and produced only a very small voltage spike. In the second of these tests, modifications dictated by results of the first were incorporated, but a failure still resulted. Four of the 5 MA should have been transferred to the fuse, but only 2 MA were. The factor of two reduction in current underscores the magnitude of our problem. This level of current translates to one-fourth the stress on the cables, and approaches one-tenth the stress on the cables in the initial test. The experiment nevertheless failed at the 100-kV level set for the surface discharge switch to close, just as it did in the prior two tests. We have pulse tested these cables to >500 kV with a fast Marx generator, and have DC hi-potted the cables prior to the test to 170 kV without failure. We are currently trying to determine the precise failure mechanism for the last of our tests, and we will proceed to LAGUNA z-pinch experiments when a transmission section that will withstand the transfer of a current pulse to our load has been developed.

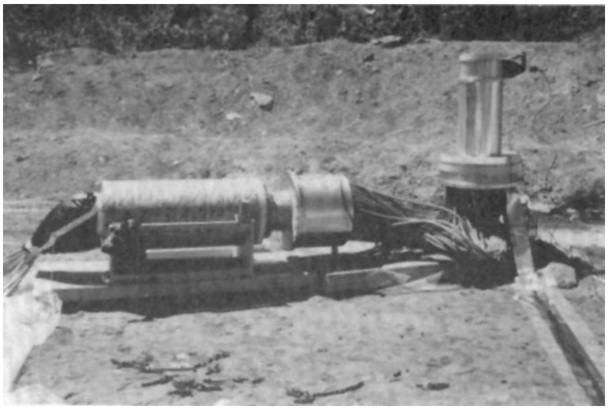

Figure 9. LAGUNA pulsed power apparatus with 72-cable transition and fuse load.

Acknowledgements

The authors wish to acknowledge the important contributions of a large number of people and sincerely hope that the reader will turn to Ref. 4 (in these proceedings) where we have devoted the space to do this properly.

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